Research Centre Rez

Experimental investigations and simulations of the control system in Supercritical CO2 loop

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CVR sCO2 related projects

- **European:**
- **GoFastR (Gas cooled Fast Reactor) / FP7 / 2010-2013**
  - Partners: AMEC, Areva, KIT, Rolls-Royce, CVR …….
  - Optimisation of sCO2 cycle for GFR reactor
- **SUSEN (Sustainable Energy) / 2012 – 2017 / sCO2 loop built**
  - Design, construction, calculations, fabrication, commissioning
  - First tests finished (TG, HXs)
- **sCO2-HeRo (sCO2 Heat Removal system) / H2020 / 2015 – 2018**
  - Partners – UDE, USTUTT, GfS, TUD, CVR, UJV,
  - Goals – sCO2 safety system for present NPP, micro-scale demonstration unite
- **sCO2-Flex / H2020 / 2018 – 2020**
  - Partners – EDF, GE, FivesCryo, USTUTT, UDE, POLIMI, CVR, UJV, CSM, ZABALA
  - Goals – design of 25MWe sCO2 cycle powered by coal fired boiler
- **sCO2-4-NPP (continuation of sCO2-HeRo) / H2020 / 2019 – 2022**
  - Partners – EDF, GE, UDE, USTUTT, GfS, CVR, UJV, JSI, ARTIC
- **National:**
- **sCO2 Efekt - demonstration unit – simple brayton cycle 1MWe / TACR / 2019-2023**
  - Partners – CVR, Doosan, Sobriety, UJV
- **sCO2 Chemistry / TACR / 2019 – 2025**
  - Partners – CVR, VSCHT
- **Energy Well - Fluoride salt cooled SMR sCO2 conversion cycle**
  - Partners – CVR, CVUT, UJV

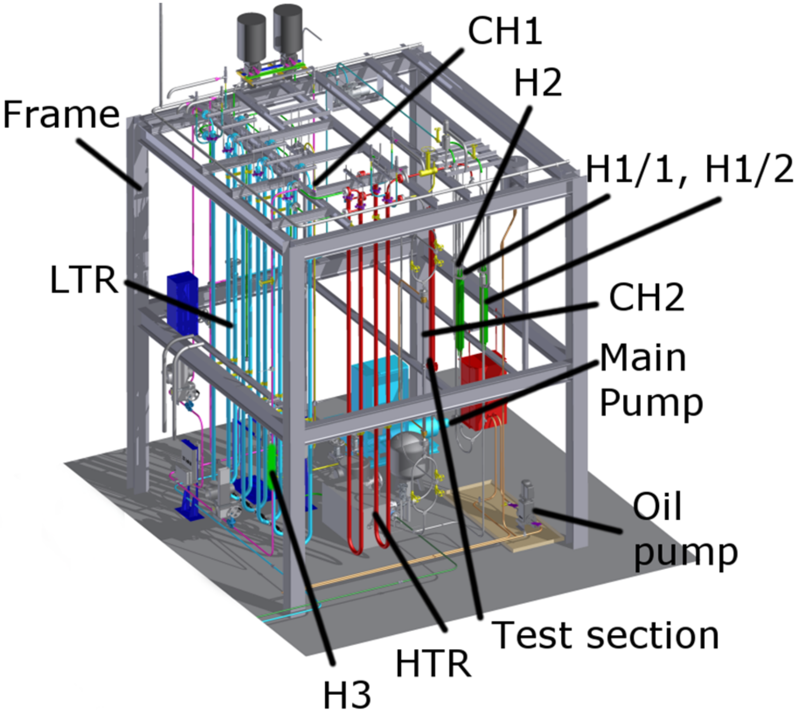
CVR sCO2 experimental loop description

- **The sCO2 experimental loop was constructed within SUSEN (Sustainable Energy) project in 2017**
- **Providing a facility to study key aspects of the sCO2 Brayton cycle (heat transfer, system dynamics, performance of compressor and turbine, corrosion, erosion etc.) with wide range of parameters: temperature up to 550°C, pressure up to 30 MPa**
- **The sCO2 loop is flexible, easy to modify and suitable for testing key components of the Brayton cycle:**
  - compressor and turbine
  - heat exchangers
  - heaters
  - Valves
- **Experimental TH data obtained from sCO2 loop is used for benchmarking, validation and further improvement of the computational codes developed.**
- **Workshops for the sCO2 community, industrial partners and students will be organized to present results and to popularize the sCO2 activities.**

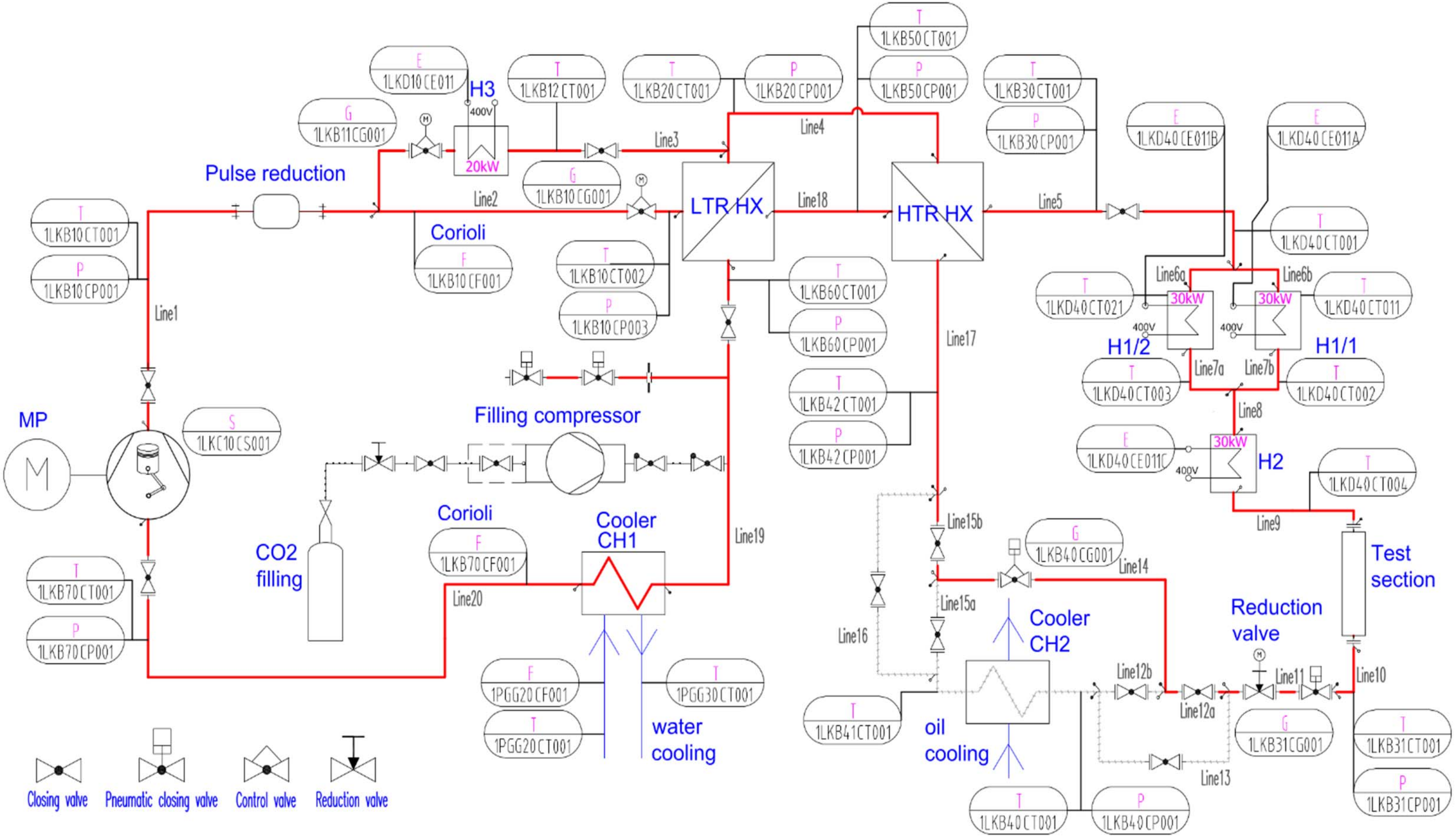
CVR sCO2 experimental loop description

- **The main operating parameters of the sCO2 primary loop**

Parameter	Value
Maximum operation pressure	25 MPa
Maximum pressure	30 MPa
Maximum operation temperature	550°C
Maximum temperature in HTR	450°C
Maximum temperature in LTR	300°C
Nominal mass flow	0.35 kg/s
Total heating power	110 KW



SUSEN sCO2 loop

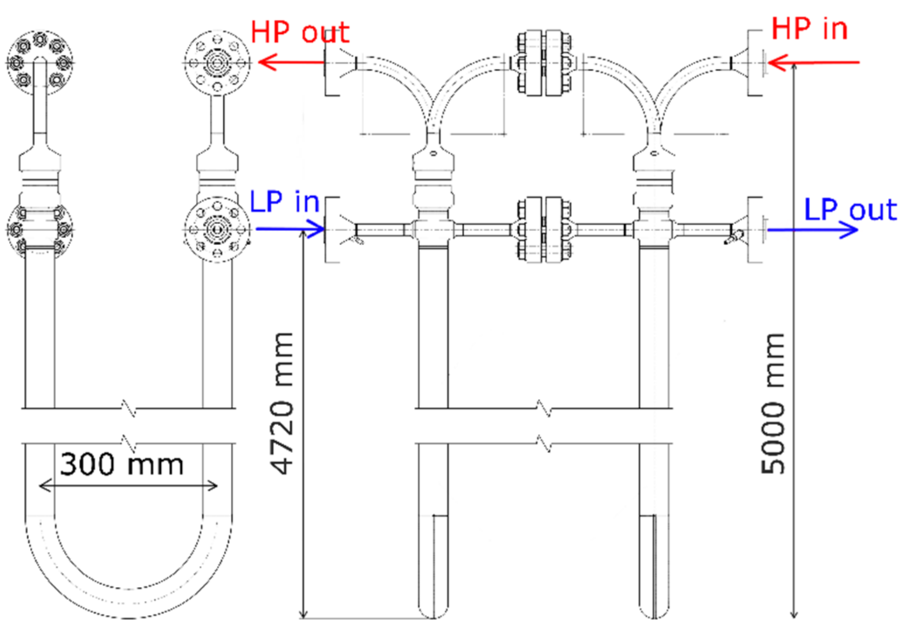


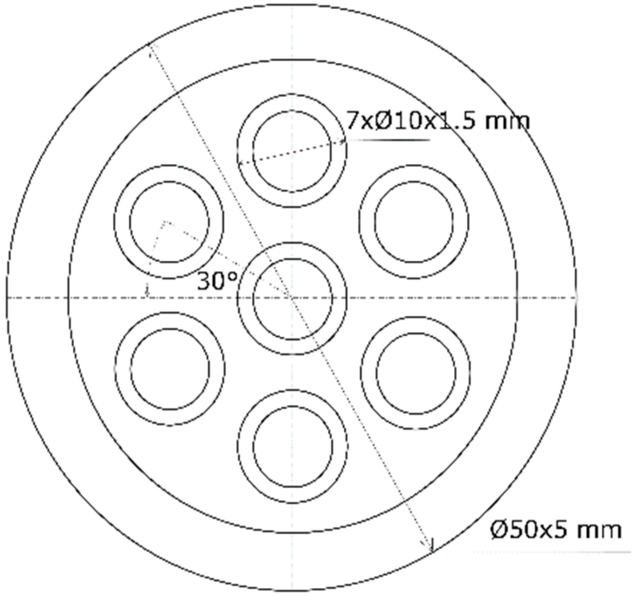
Motivation

- **A number of investigators have carried out extensive experimental tests and analyses of sCO2. However, their work is rather limited to the component behavior studies, i.e. heat transfer and pressure drop models in heaters/coolers/heat exchangers PETUKHOV (1961), *PIORO (2005)***
- **Very few data can be found on operation and analysis of compressors and turbines *WRIGHT (2010), UTAMURA (2012)***
- **What is missing is simulation tool which is validated on models of the system level (component interaction) on both steady states and dynamic transients including control system interactions.**
- **The main objective of this work:**
  - provide evidence that the open source **Modelica-based code ClaRa** is suitable for modeling
    - steady states
    - transients
    - Transients with PID controllers’ actions and their tuning in sCO2 environment
- **Relevant boundary condition are given in the paper such as a detailed description of the experimental facility (loop geometry, p,T, Q_flow and m_flow etc.) to allow preparation of the computational models.**

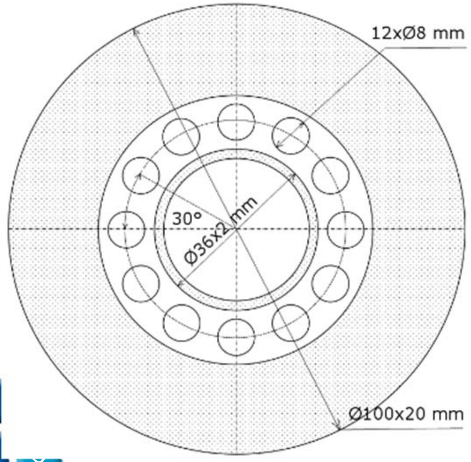
Geometry - example

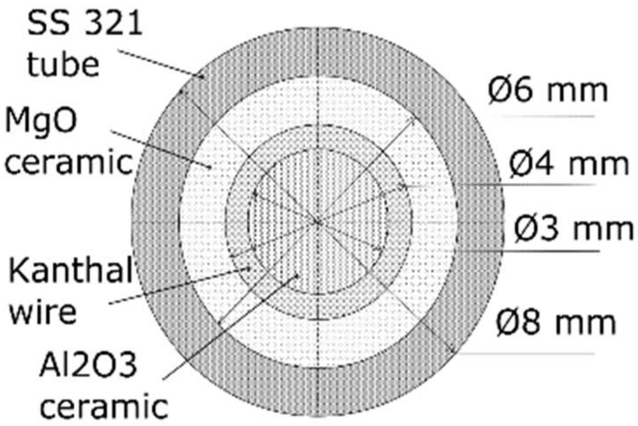
LTR/HTR



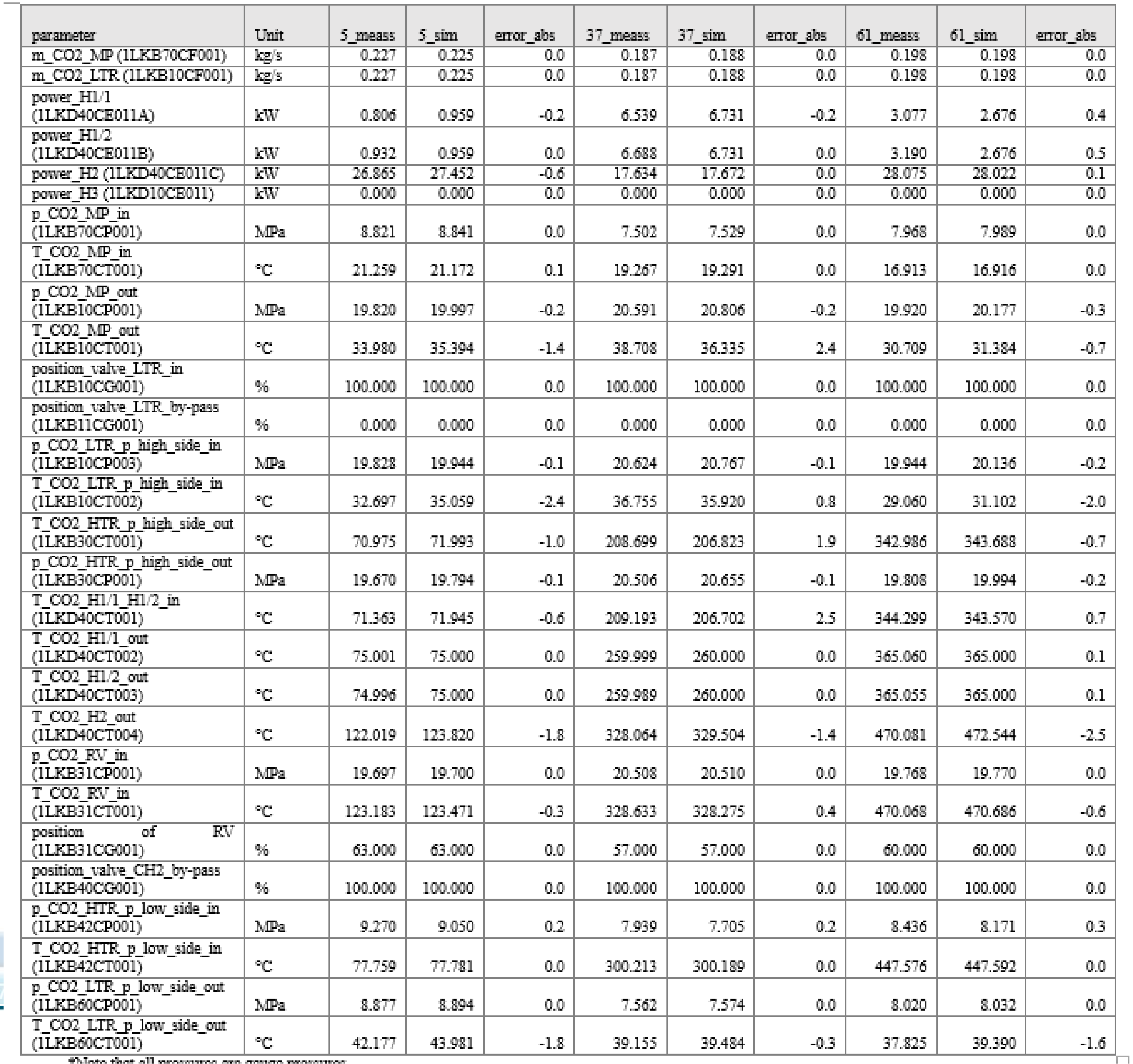


Electric heater





Meassured and calculated steady state parameters

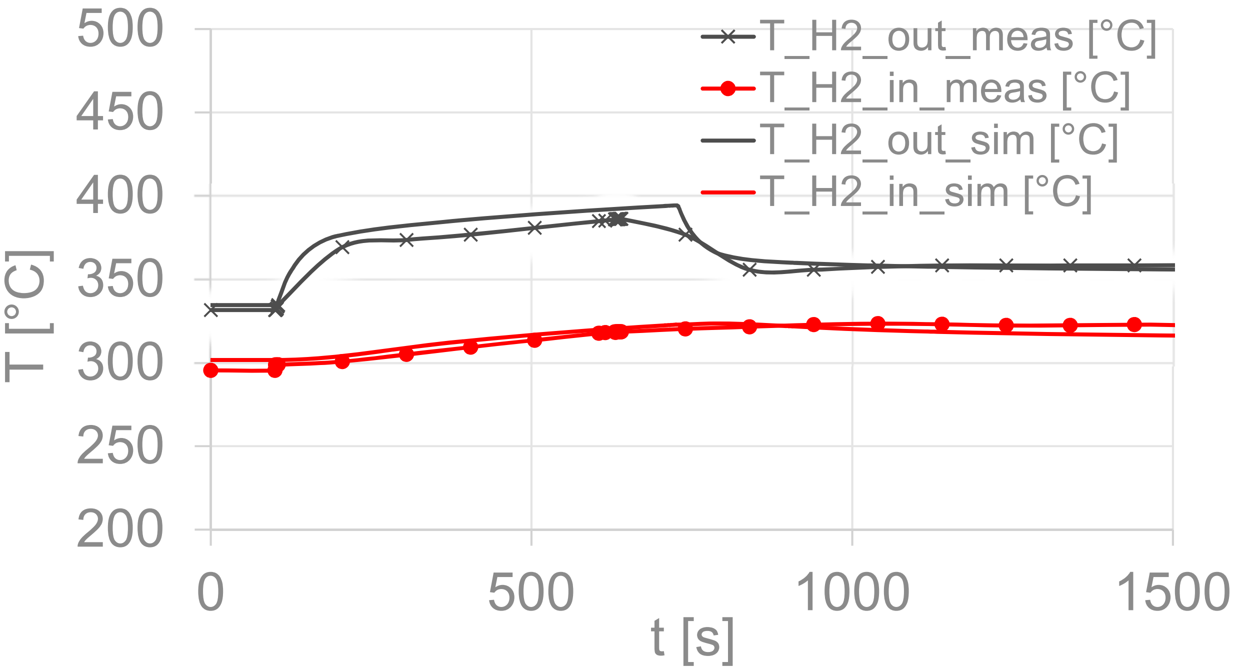


parameter	Unit	5_meass	5_sim	error_abs	37_meass	37_sim	error_abs	61_meass	61_sim	error_abs
m_CO2_MP (1LKB70CF001)	kg/s	0.227	0.225	0.0	0.187	0.188	0.0	0.198	0.198	0.0
m_CO2_LTR (1LKB10CF001)	kg/s	0.227	0.225	0.0	0.187	0.188	0.0	0.198	0.198	0.0
power_H1/1 (1LKD40CE011A)	kW	0.806	0.959	-0.2	6.539	6.731	-0.2	3.077	2.676	0.4
power_H1/2 (1LKD40CE011B)	kW	0.932	0.959	0.0	6.688	6.731	0.0	3.190	2.676	0.5
power_H2 (1LKD40CE011C)	kW	26.865	27.452	-0.6	17.634	17.672	0.0	28.075	28.022	0.1
power_H3 (1LKD10CE011)	kW	0.000	0.000	0.0	0.000	0.000	0.0	0.000	0.000	0.0
p_CO2_MP_in (1LKB70CP001)	MPa	8.821	8.841	0.0	7.502	7.529	0.0	7.968	7.989	0.0
T_CO2_MP_in (1LKB70CT001)	°C	21.259	21.172	0.1	19.267	19.291	0.0	16.913	16.916	0.0
p_CO2_MP_out (1LKB10CP001)	MPa	19.820	19.997	-0.2	20.591	20.806	-0.2	19.920	20.177	-0.3
T_CO2_MP_out (1LKB10CT001)	°C	33.980	35.394	-1.4	38.708	36.335	2.4	30.709	31.384	-0.7
position_valve_LTR_in (1LKB10CG001)	%	100.000	100.000	0.0	100.000	100.000	0.0	100.000	100.000	0.0
position_valve_LTR_by-pass (1LKB11CG001)	%	0.000	0.000	0.0	0.000	0.000	0.0	0.000	0.000	0.0
p_CO2_LTR_p_high_side_in (1LKB10CP003)	MPa	19.828	19.944	-0.1	20.624	20.767	-0.1	19.944	20.136	-0.2
T_CO2_LTR_p_high_side_in (1LKB10CT002)	°C	32.697	35.059	-2.4	36.755	35.920	0.8	29.060	31.102	-2.0
T_CO2_HTR_p_high_side_out (1LKB30CT001)	°C	70.975	71.993	-1.0	208.699	206.823	1.9	342.986	343.688	-0.7
p_CO2_HTR_p_high_side_out (1LKB30CP001)	MPa	19.670	19.794	-0.1	20.506	20.655	-0.1	19.808	19.994	-0.2
T_CO2_H1/1_H1/2_in (1LKD40CT001)	°C	71.363	71.945	-0.6	209.193	206.702	2.5	344.299	343.570	0.7
T_CO2_H1/1_out (1LKD40CT002)	°C	75.001	75.000	0.0	259.999	260.000	0.0	365.060	365.000	0.1
T_CO2_H1/2_out (1LKD40CT003)	°C	74.996	75.000	0.0	259.989	260.000	0.0	365.055	365.000	0.1
T_CO2_H2_out (1LKD40CT004)	°C	122.019	123.820	-1.8	328.064	329.504	-1.4	470.081	472.544	-2.5
p_CO2_RV_in (1LKB31CP001)	MPa	19.697	19.700	0.0	20.508	20.510	0.0	19.768	19.770	0.0
T_CO2_RV_in (1LKB31CT001)	°C	123.183	123.471	-0.3	328.633	328.275	0.4	470.068	470.686	-0.6
position of RV (1LKB31CG001)	%	63.000	63.000	0.0	57.000	57.000	0.0	60.000	60.000	0.0
position_valve_CH2_by-pass (1LKB40CG001)	%	100.000	100.000	0.0	100.000	100.000	0.0	100.000	100.000	0.0
p_CO2_HTR_p_low_side_in (1LKB42CP001)	MPa	9.270	9.050	0.2	7.939	7.705	0.2	8.436	8.171	0.3
T_CO2_HTR_p_low_side_in (1LKB42CT001)	°C	77.759	77.781	0.0	300.213	300.189	0.0	447.576	447.592	0.0
p_CO2_LTR_p_low_side_out (1LKB60CP001)	MPa	8.877	8.894	0.0	7.562	7.574	0.0	8.020	8.032	0.0
T_CO2_LTR_p_low_side_out (1LKB60CT001)	°C	42.177	43.981	-1.8	39.155	39.484	-0.3	37.825	39.390	-1.6

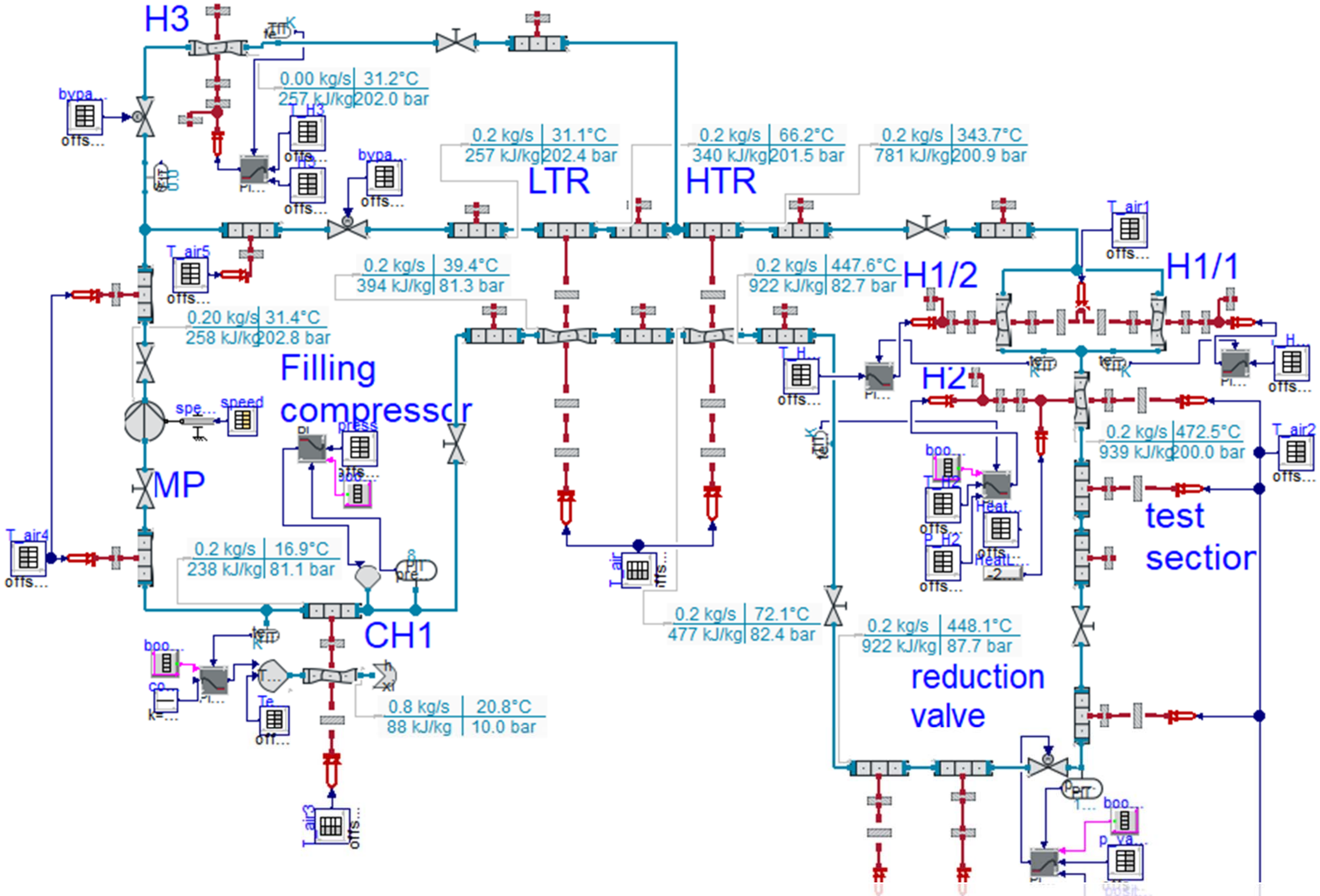
*Note that all pressures are gauge pressures

Meassured and calculated steady state parameters

- As a part of experimental campaign, three steady states were selected (covering different temperature levels and pressures – p_low/p_high ~ 7÷9/20 MPa, T_low/T_high ~ 15÷20/100÷500 °C) in order to benchmark the numerical model at first place.
- Several transients have been considered to assess the models in dynamic conditions. Such as:
  - loss of heat sink
  - sudden change of mass flow rate
  - sudden change of heating


Temperature at heater during sudden change of heating power

sCO2 SUSEN loop in ClaRa – steady state



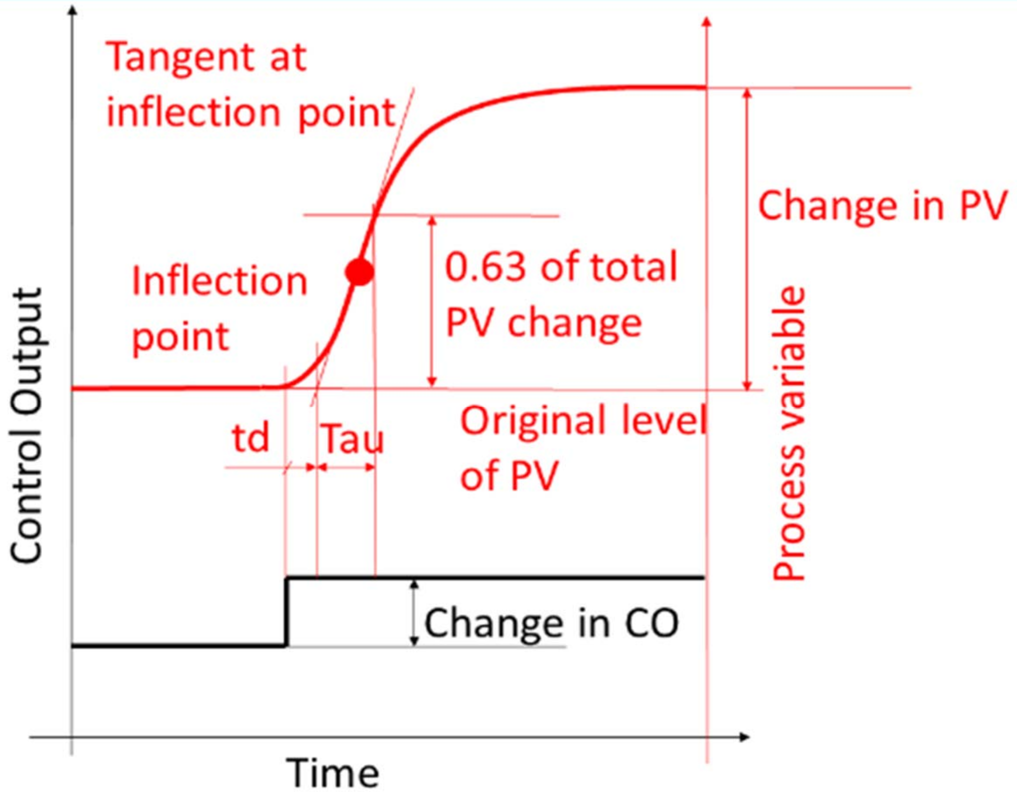
- **The simulated results show fair agreement, demonstrating reasonable accuracy of the simulation tool. There are maximum 2.5 K/0.2 MPa/0.6 kW temperature/pressure/heating power errors respectively.**

Tuning of PID controllers

- Once the numerical model was cross-checked, the tuning procedure of the PID controllers was performed.
- Currently the PID algorithm is the most popular feedback controller used in industry.
- Many tuning techniques have been developed over the past several decades.
- Cohen-Coon tuning rules is one of the most used technique in industry since it is suited to a wider variety of processes.
- Important: Knowing the form of the algorithm used for the PID controller tuning (The main PID structures (Interactive, <u>Non-interactive</u> and parallel).

$$CO = K_c \cdot \left(e(t) + \frac{1}{T_i} \int e(t)\, dt + T_d \frac{de(t)}{dt} \right)$$

Tuning of PID controllers



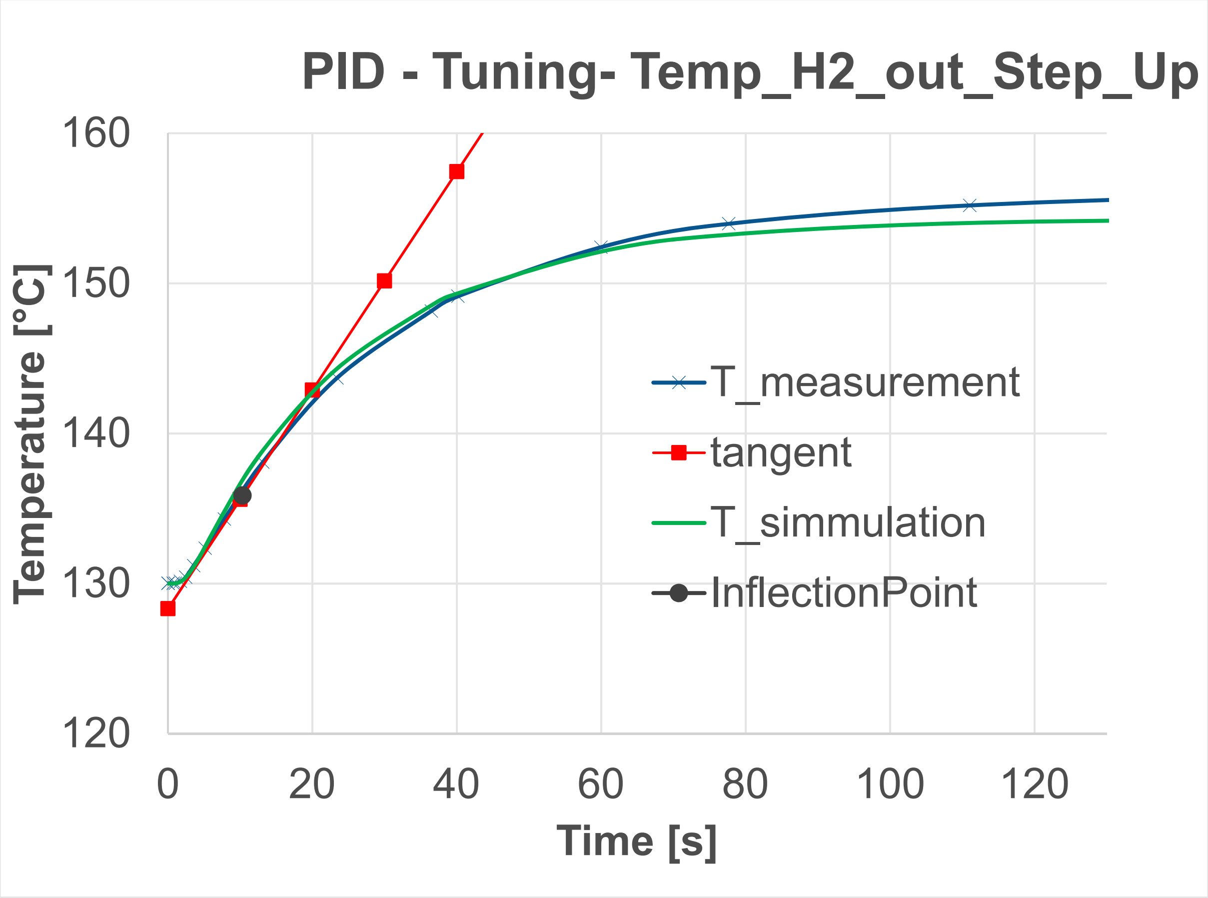
Tau time constant [s]
td dead time [s]

$$GP = \frac{\text{change in PV [\%]}}{\text{change in CO [\%]}}$$

	K_c	T_i	T_d
P controller	$\frac{1.03}{GP}\left(\frac{Tau}{td} + 0.34\right)$		
PI controller	$\frac{0.9}{GP}\left(\frac{Tau}{td} + 0.092\right)$	$3.33td\left(\frac{Tau + 0.092td}{Tau + 2.22td}\right)$	
PD controller	$\frac{1.24}{GP}\left(\frac{Tau}{td} + 0.129\right)$		$0.27td\left(\frac{Tau - 0.324td}{Tau + 0.129td}\right)$
PID controller	$\frac{1.35}{GP}\left(\frac{Tau}{td} + 0.185\right)$	$2.5td\left(\frac{Tau + 0.185td}{Tau + 0.611td}\right)$	$0.37td\left(\frac{Tau}{Tau + 0.185td}\right)$

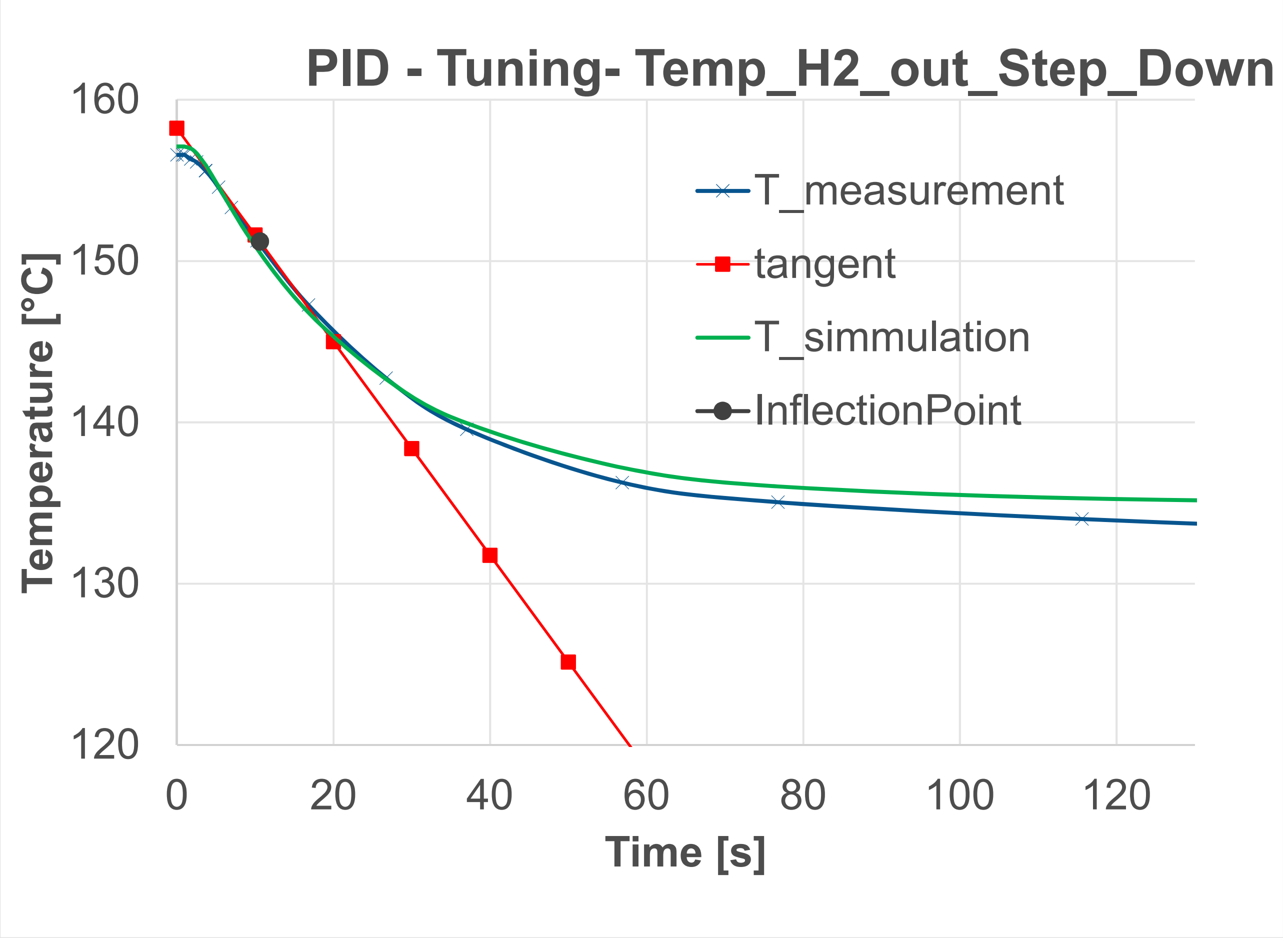
Tuning of PID controllers and comparison with measured data

- ***Step-up***
- **Firstly, a sudden step-up increase in H2 power output (from initial 6.2 kW to final 10.9 kW) was initiated at stable system. The response curve of the process variable (temperature)**



Tuning of PID controllers and comparison with measured data

- ***Step-down***
- **In order to verify the first test, second step test was conducted after the stabilization of parameters in the system. A sudden step-down decrease in H2 power output (from initial 10.9 kW to final 6.6 kW) was initiated at stable system. The response curve of the process variable (temperature)**



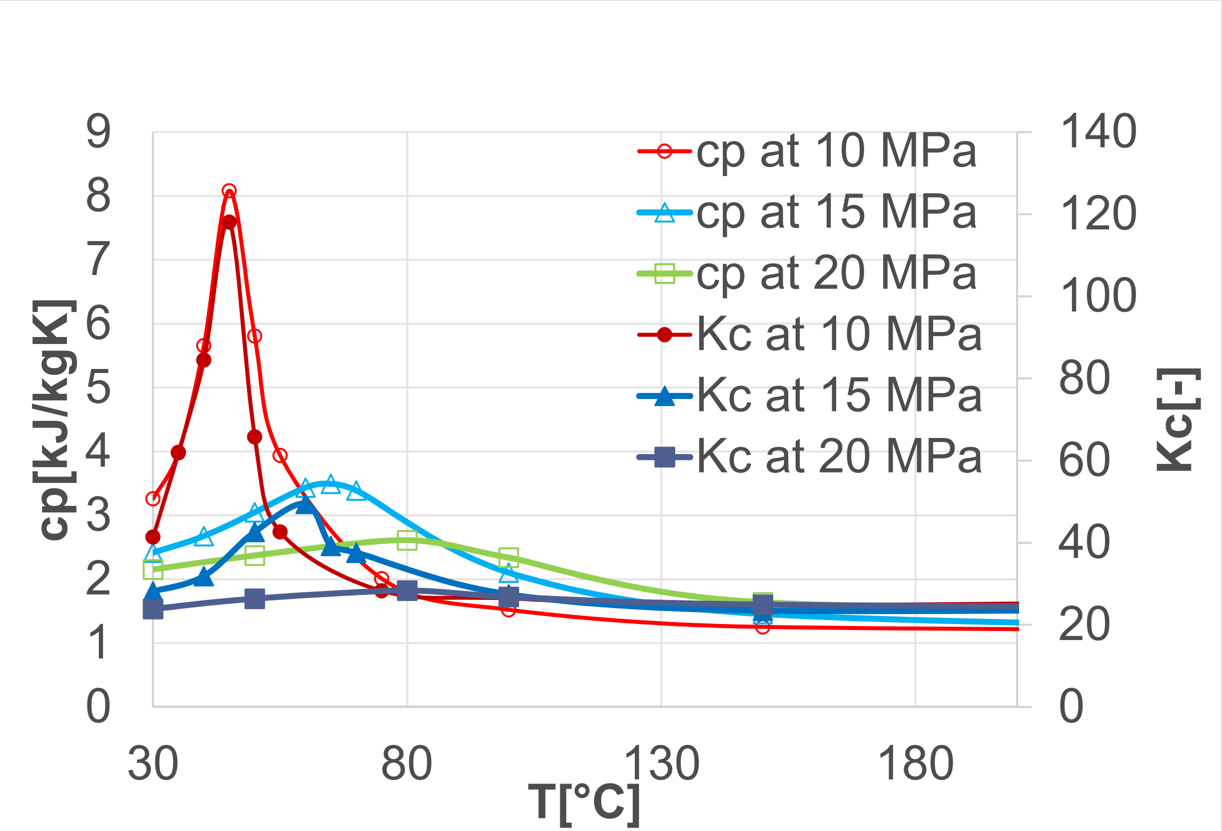
Tuning of PID controllers and comparison with measured data

- PID tuning settings for measured and simulated data

	Kc	Ti	Td
Step-up test – measured	29.14	5.60	0.85
Step-down test - measured	26.79	5.97	0.90
Average - measured	27.96	5.79	0.88
Step-up test – simulated	26.79	5.35	0.81
Step-down test - simulated	26.33	5.24	0.79
Average - simulated	26.56	5.30	0.80

Tuning of PID controllers for multiple Process conditions

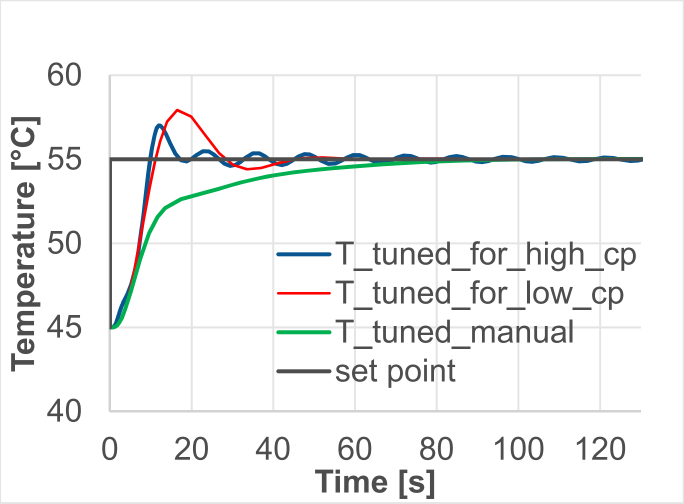
- **Fluid properties of the sCO2 near the critical point experiences highly non-linear variations - challenges for modeling, and exhibits unique behavior during transients which greatly complicate the control of the system**
- **To demonstrate that series of response curves with different conditions (pressure 10 MPa ÷ 20 MPa, temperature 30 °C ÷ 400 °C) were simulated and tuning constants of the PID controller were derived using Cohen-Coon method for each case.**

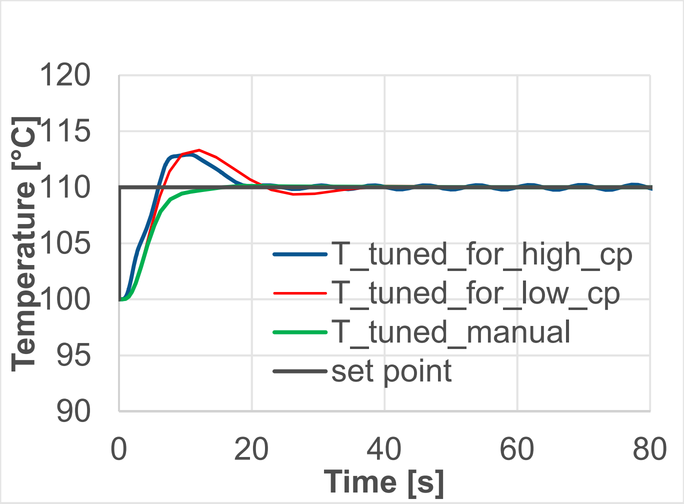


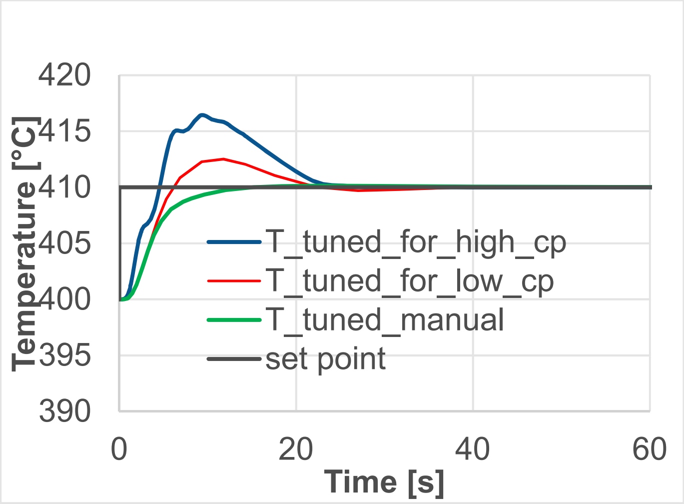
- cp is peaking at so called pseudo-critical temperatures and similarly the **controller gains Kc**.
- **integral** and **derivative** time constants **did not varied significantly** and stayed in a relatively small range (Ti = 4 s ÷ 6 s and Td = 0.6 s ÷ 1 s)

Testing of settings

- **Once the new sets of PID controller were derived, they were tested on several examples.**
- **Testing of behavior of PID controller of the temperature outlet from H2 during the step change of set point (10 K). For demonstration, two extreme PID sets were chosen together with manually tuned constants.**
  - parameters tuned for the highest cp approx. 8 kJ·kg^{-1}·K^{-1} (Kc=118, Ti=3.7 s, Td=0.6
  - lowest cp approx. 1 kJ·kg^{-1}·K^{-1} (Kc=25, Ti=5 s, Td=1 s)
  - manually tuned PID following constants (Kc=25, Ti=20 s, Td=1 s)







- **process variable, controlled by PID with settings tuned for high cp, exhibits comparatively high overshoots and instabilities, especially for the higher temperatures test cases (above 100°C). Improvement can be seen for the low cp tuning. It still exhibits quite high overshoots, however the oscillations were significantly reduced. The manually tuned controller behaves well for all 3 tested temperatures.**

Conclusion

- Dynamic model of sCO2 was created using ClaRa
- Firstly, numerical model was checked with experimental data on steady/transients states
- Secondly, transient tests covering the tuning procedure of the PID controllers were performed. The scope of the study is to give a first approximation of tuning parameters of such a system. For this purpose, one of the most utilized tuning technique, the Cohen-Coon (C-C) method, was deployed.
- The discrepancy of the PID sets derived from simulations and experiment is within 10%.
- Different settings of PID controller were tested on several examples. It has been found that the tuned PID constants according to C-C method exhibits relatively high overshoots. It is due to the fact that different tuning techniques gives preferences to fast response prior to stable behavior. The results from the study indicates that C-C method prefers fast response.

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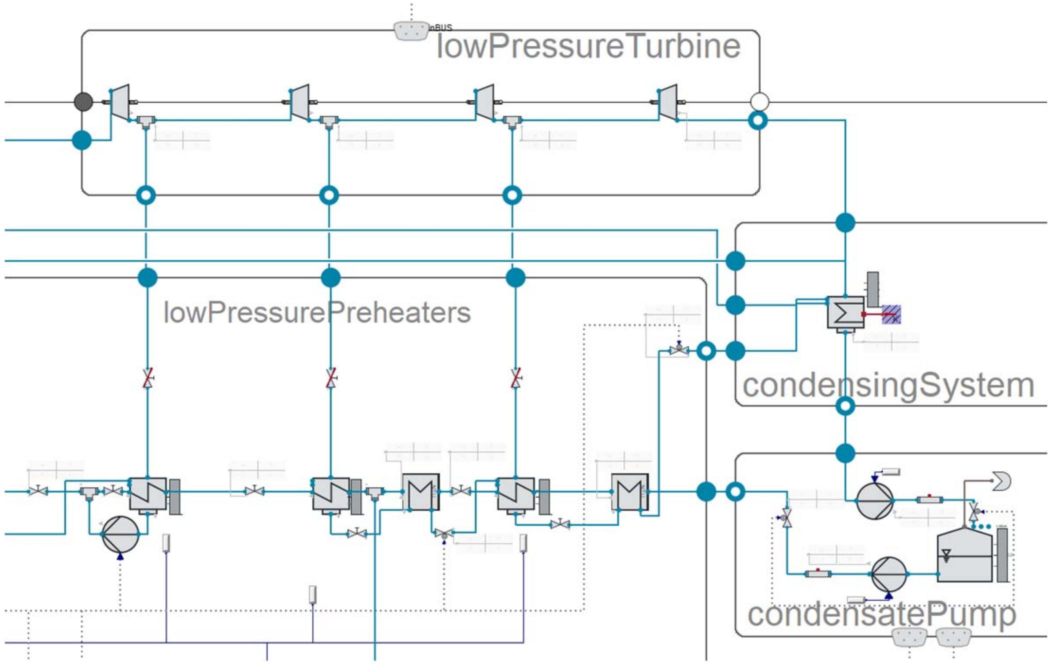

Backup

- **The I&C is built on integrated control system environment ABB FREELANCE with ABB – AC900F control units and S800 I/O modules directly attached on terminal units (for binary signals) and Siemens ET200M (for analog signals).**